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ESTIMATING SOIL MOISTURE CONDITIONS AND TIME FOR IRRIGATION WITH THE EVAPOTRANSPIRATION METHOD

by

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1. Justification

A knowledge of the moisture content of the soil is indispensable in irrigation experiments, in field experiments in general, and in irrigation practice on the farm. Measurement of soil moisture content has received much attention in the past and, at the present time, new emphasis upon this problem is evident. In spite of all the work that has been done, no single satisfactory method has been produced. A satisfactory method is one whereby moisture content can be found rapidly, accurately, and repeatedly on the same location without undue expense of time and money.

Given sufficient time and funds, it is possible to characterize soil moisture conditions by any one of a number of methods, but in many irrigation experiments and other field applications, there is no opportunity nor justification for setting aside a major part of the available resources for what is only a facet of the over-all problem. This report presents information which is needed to estimate soil moisture content through the use of climatological data.

It is not the intent of this report to imply that other methods of soil moisture measurement are not suitable or less accurate than the procedure suggested here. It is merely intended to make the required information available to those who wish to try out a relatively new approach to the problem.

In the majority of investigations dealing with soil, water, and crop response, the moisture content of a layer of soil is characterized. Usually, this is the layer of soil from which the major part of the water dissipated by the plants originates. The moisture content of this so-called rootzone changes rapidly during the season between two extremes of ultimate wetness and ultimate dryness. At the ultimate moisture contents, the rootzone is quite uniform, but anywhere in between, great variability is the rule. The distribution of moisture content within the rootzone is not of primary significance, but rather the total, or average, content of water.

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It is not the moisture content of the soil that determines its availability to plants, but, rather, the tenacity with which it is held. Commonly, this property of the soil water is referred to as its stress, and it is measured in pressure units such as atmospheres. But, in characterizing soil moisture availability, the average stress must be used, recognizing at the same time that widely different stress values coexist in the rootzone.

Except in more refined plant behavior studies, gross figures are sought which describe the over-all situation in the rootzone. It would be erroneous to conclude from this statement, however, that a few spot checks of moisture content or stress give the required information. A complete schedule of sampling depths and times must be maintained, or seriously misleading information may be expected.

It would seem advantageous to employ a method in which the root zone is examined as a whole, such as the evapotranspiration method.

2. Principle of the Method

The evapotranspiration method embodies several laws and experiences from the fields of plant physiology, soil science, and meterology, but the two most important principles are these.

1. When soil moisture is plentiful, evapotranspiration depends primarily upon weather conditions.

2. The moisture content of the rootzone at a given time equals that at a previous time, plus the difference between income and outgo over the period elapsed (conservation of matter).

It is possible, therefore, by applying these principles to find the moisture content of the rootzone through a measurement or an estimate of gains and losses of water. In the following the method is discussed in detail.

2.1 The soil water reservoir

In using the evapotranspiration method, the total amount of plant-available water rather than the moisture content of the soil or the tension of the soil water are of direct concern. The total amount of plant-available water is extensive or quantitative, giving definite information directly applicable in an engineering problem.

The total amount of plant-available water at any time is determined by the following three factors.

1. The soil moisture content by solume at field capacity.

2. The depth to which roots extend.

3. The soil moisture content by volume at which water is no longer available to plants.

Properties (1) and (3) usually depend upon depth. Further, item (2) depends upon the nature of the crop and of the soil, and also, in some cases, upon the stage of development of the crop. When there is an appreciable dependence upon depth of items (1) and (3), the usual procedure is to evaluate them horizon by horizon, and to average the values, weighing each with the thickness of the horizon.

Information about the depth of root extension and water extraction is often not easily available. Ordinarily, estimates derived from visual inspection of root systems or generalization of accurate measurements such as are reported in the literature are used.

The quantity that is needed in using the evapotranspiration method is the maximum amount of plant-available water in the rootzone.

Item (1) above is then represented by the field capacity moisture content on a volume basis. It is best determined by a sampling of the profile after a heavy rain or irrigation for moisture content by weight and for bulk density.

Item (2) above already has been mentioned. Usually, the thickness of the rootzone is found by inspection. Careful study of changes in moisture content of the soil profile during prolonged dry periods is probably the most desirable method to find the rootzone thickness for the present purpose. Often, this method will require much time and effort.

The limit of water availability, item (3) above, is ordinarily gaged from a knowledge of the so-called wilting percentage. In reality, there is a wilting range which seems to depend upon soil and plant factors. For reasons of expediency, the concept of the wilting percentage is a good one. The error that may be entailed by using this concept seems actually to be quite minor compared to errors that can arise in the estimation of items (1) and (2).

The wilting percentage is usually identified with the fifteen-atmosphere-percentage (FAP) of disturbed samples of soil as it is determined with pressure cells. Since this figure is expressed on a dry weight basis, it is necessary to know the bulk density in order to find the corresponding moisture content by volume.

Information on the wilting percentage can also be obtained by periodic sampling of the profile during prolonged dry periods. These data should be no means be considered inferior to such as are obtained with pressure cells.

The figure for the maximum amount of plant-available water may be obtained by multiplying the difference between field capacity and wilting percentage, both expressed on a volume basis with the depth of the root-zone in inches, thus arriving at the result expressed in inches of precipitation equivalent.

Of course, in some investigations or applications, the amount of plant-available water is not figured from the wilting percentage, but from higher moisture content corresponding to a lower stress. In such a case, a knowledge of the moisture characteristic of the soil is required, but the calculation is the same. In other cases, the available water is defined as a certain fraction of the total available amount as figured from the wilting percentage. Whichever method is followed makes no difference in using the evapotranspiration method.

2.2 Measuring rainfall

Daily measurement of rain at the site of interest is indispensable in the evapotranspiration method. Since rainfall measurement is critical, it is important to see that the raingage is located away from interfering objects such as buildings, posts, trees and high vegetation.

The raingage should be read daily and, for reasons that will be apparent later, preferably early in the morning.

2.3 Estimating evapotranspiration

This is, understandably, the other critical aspect of the evapotranspiration method. It would never be possible to make adequate estimates of the amount of evapotranspiration if it were not for the fact that a conservative process is dealt with. That is, first of all, on any day its intensity is bounded by definite limits. These limits are zero and a maximum value which depends upon latitude and time of the year, but which never and nowhere exceeds a value of about 0.35 inch per day.

Second, evapotranspiration is principally dependent upon incident radiative energy. The value of the latter is determined in first instance by factors that are astronomical and geographical and, therefore, precisely predictable. Cloudiness also controls incident energy, and it tends to vary from day to day in an unpredictable fashion. It is not too difficult to measure cloudiness or sunshine duration.

The daily average air temperature is to be determined in a standard shelter at the location of the experiment.

Having procured these two values, the nomogram on page 16 is ready for use. First, from Table 3, the proper value of the extraterrestial radiation is found and this value is marked on the left hand scale. This point is connected with the value for the sunshine percentage with a straightedge and the point of intersection with the central line is marked. Finally, the latter point of intersection is connected with the value for average air temperature with the use of the straightedge, and the value for daily evapotranspiration is read from the right hand scale.

2.4 Method of computation

Having at hand daily values for rainfall and estimated evapotranspiration and an estimate of the maximum amount of available soil water, the computations are carried out as follows.

In the beginning of each day the available water in the rootzone is estimated from the corresponding amount on the previous day, minus the amount of estimated evapotranspiration, and plus the amount of rainfall for the previous day. Since there is little, if any, evaporation during the night, an early morning hour is the best reference hour for the calculations. Pertinent weather information for the previous day (24 hour period) can also be conveniently obtained at that time, such as rainfall, sunshine duration, maximum and minimum temperature. In order to have a convenient and reliable beginning point for the daily calculation of the soil water balance, the computations are begun on a day that follows a heavy rain or irrigation. The starting amount is then the maximum water holding capacity of the rootzone.

Sometimes a rain will be large enough so as to cause the balance to exceed the maximum capacity, in which case the excess is to be canceled. This operation represents the fact that excess moisture over field capacity will be disposed of by deep percolation or subsurface runoff. In some cases, this process will take more than the 24 hour period which is implied by the calculation, but no serious error is thus incurred.

When the balance is zero or less, a total depletion of the soil moisture reservior is indicated. On days on which such a condition prevails, the evapotranspiration rates are assumed to be zero, and any negative results are canceled. In reality, of course, there will be a continued, if much smaller rate, of water loss. Actually, though, this is an irrevelant matter since irrigation should be applied immediately as the zero condition arises. In other words, irrigation is to be carried out on the same day a zero or negative balance is obtained.

Another factor which is significant for evapotranspiration is the air temperature. This is principally explained by the fact that warm air can contain more water in vapor form than cold air.

Windspeed and relative humidity are of minor significance for the evapotranspiration of large homogeneous areas, all popular opinion to the contrary. Suffice it to mention that all theoretical and experimental studies have so far supported the statement above.

In arriving at daily estimates of evapotranspiration, there appear two practical solutions, a choice of which depends upon the precision desired. Both solutions are based upon the Penman formula, which so far appears to give reasonable predictions for the Eastern part of the United States.

2.3.1 Use of general tables

For on-the-farm use or for use in experiments where irrigation is just another good management practice and not an object of investigation, the use of general tables of evapotranspiration values is suggested. Factors taken into account when using this approach are: time of the year (to the nearest month), geographical location (to the nearest 10 degrees), and general weather conditions during the day (three categories).

Obviously, this is not a refined method, but it has the great advantage that all calculations and measurements, except rainfall, have been eliminated. A mere consultation of the table is all that is required. The table is given in the Appendix as Table 1.

2.3.2 Use of Penman's formula with simplified nomogram.

Often precision is required greater than may be achieved with the table suggested in section 2.3.1. In studies of plant response to soil moisture this would certainly be the case.

Use of the complete Penman formula (see Appendix, section 4.6) involves considerable labor of calculation and the use of several meteorological instruments which are to be read daily. In order to obviate the objections, at least partially, a nomogram has been prepared which is based upon the measurement of the two most important weather variables: radiation and air temperature.

Specifically, one needs a daily value for the so-called sunshine percentage and a daily value for the average air temperature at standard height. In order to find the sunshine percentage, the number of hours of sunshine must be measured. Details on this measurement are given in the Appendix. Once the daily number of sunshine hours is know, sunshine percentage is found by dividing the former value by the total possible hours of sunshine. Values for the latter are given in Table 2 of the Appendix.

No recognition is given to the possibility of surface runoff in the method. The reason is obviously that the quantity of surface runoff cannot easily be estimated. Investigations have shown, however, that the error incurred by ignoring runoff is not very serious.

The method of computation, as it is given, is an approximate one, just like the other components as soil water storage and evapotranspiration are approximated. As a whole, the method does not represent an exact tool, that is, it does not incorporate the latest findings, and the best instrumentation. The evapotransipration method is a compromise between the demands for dependable information and the practical limitations to what can be done under field conditions.

The method is applicable in the Eastern United States because:

a/ Soil moisture holding capacities are, generally, limited.
b/ Frequent rains occur during the growing season.
c/ Each year during the winter months the rootzone is fully replenished with moisture.

The three factors above minimize the errors that are a part of the assumptions made. In many Western areas, the three conditions listed above are often not met, and the evapotranspiration method may not be applicable there. In the following section the method is to be illustrated with two examples.

3. Examples of method

3.1 Use of general tables

The first example is based on the use of the general table, and is assumed to apply to a farm irrigation problem in North Carolina. Pertinent information has, therefore, been taken from the North Carolina Irrigation Guide as prepared by SCS.

The example is irrigation of mixed hay on Portsmouth sandy loam in North Carolina. The depth of moisture replacement is given 1.5 feet and the available moisture holding capacity to that depth as 2.4 inches. If 50 percent of this is assumed to be readily available, we find a moisture storage capacity figure basic to the use of the evapotranspiration method.

Calculations are now shown in the following table, the estimated values for evapotranspiration having been taken from Table 1 in the Appendix.

Date	Weather	Conditions on Previous Day Rain	 Irrigation	 Evapotranspiration	Today at 8:AM Balance
June 1	Cloudy	3.00	-	0.14	1.20
" 2	Fair	-	-	0.17	1.03
" 3	Fair	-	-	0.17	0.86
" 4	Fair	-	-	0.17	0.69
" 5	Bright	-	-	0.23	0.46
" 6	Cloudy	.045	-	0.14	0.77
" 7	Bright	-	-	0.23	0.54
" 8	Bright	-	-	0.23	0.31
" 9	Bright	-	-	0.23	0.08
" 10	Fair	-	-	0.17	-0.09*
" 11	Fair	-	1.60**	0.17	1.20
" 12	Fair	-	-	0.17	1.03
" 13	Fair	-	-	0.17	0.86
" 14	Cloudy	-	-	0.14	0.72
" 15	Cloudy	1.40	-	0.14	1.20

*The negative amount indicates that irrigation must be applied on the same day.

**This amount is as suggested in the Irrigation Guide, based on 75 percent efficiency of application.

3.2 Use of calculated estimates

While the general method followed here is the same as under 3.1, the estimated values of evapotranspiration are obtained in a more complicated manner. The method followed should be self-explanatory from the following table, which applies to observations at Raleigh, N. C., latitude 35°47'.

After the values shown in the last column have been determined, the calculation is carried out exactly as demonstrated in the previous section.

Date	Sunshine Hours	Total Possible 1)	Extrat. Radiat.2)	Sunshine Percent	Av.Air Temp.	Est. E.T.3)
Sep 1,'53	7.2	13.0	.537"	55	81°F	0.12"
Sep 6,'53	0.0	12.7	.526"	0	69°F	0.01"
Sep 16,'53	12.3	12.3	.507"	100	80°F	0.19"
Sep 21,'53	4.8	12.1	.484"	40	77°F	0.08"
Sep 22,'53	12.1	12.1	.480"	100	64°F	0.14"
Sep 25,'53	0.0	11.9	.468"	0	65°	0.01"

1) Taken from Table 2, using linear interpolation
2) Taken from Table 3, using linear interpolation
3) Using the nomogram on page 16

4. Appendix

4.1 Tables

Table 1. Estimated values of daily evapotranspiration.

Table 2. Hours from sunrise to sunset.

Table 3. Extraterrestial radiation.

4.2 Rain Gages

Rain can be measured reliably with a number of different types of gages. Many projects use the U. S. Weather Bureau standard 8-inch gage, either the regular kind or recording.

Smaller and cheaper gages can be equally satisfactory for the present purpose. See the following reference:

> C. H. M. van Bavel and L. A. Forrest. A comparison of a small raingage with a standard raingage. ARS-SWCRB. Special Report No. 70, 1956.

4.3 Air temperature measurement.

Average air temperature during the day can be obtained with sufficient precision in two ways. The average of the two readings of a minimum-maxium thermometer is usually very close to the true average for the day. This is undoubtedly the simplest and cheapest method.

A thermograph can also be used. By reading hourly values from the chart and averaging these for the day, a quite precise average value is obtained. Thermographs are more expensive and require more work than do minimum-maximum thermometers.

Table 1. Estimated values of daily evapotranspiration

	Dull, Cloudy Weather	Normal Weather	Bright, Hot Weather
Latitude between 40° and 34°			
Apr. or Sep.	0.08	0.11	0.14
May or Aug.	0.11	0.14	0.19
Jun. or Jul.	0.14	0.17	0.23
Latitude between 34° and 30°			
Apr. or Sep.	0.09	0.13	0.16
May or Aug.	0.13	0.16	0.22
Jun or Jul	0.14	0.17	0.23

Table 2. HOURS FROM SUNRISE TO SUNSET*)

MONTH	LATITUDE 26°	28°	30°	32°	34°	36°	38°	40°	42°	44°	46°	48°
JAN.	10.7	10.5	10.4	10.2	10.1	10.0	9.8	9.6	9.4	9.3	9.1	8.9
FEB.	11.2	11.2	11.1	11.0	10.9	10.8	10.7	10.6	10.5	10.4	10.3	10.2
MAR.	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	11.9	11.9	11.9
APR.	12.7	12.8	12.8	12.9	13.0	13.0	13.1	13.2	13.3	13.4	13.5	13.7
MAY	13.3	13.4	13.6	13.8	13.9	14.0	14.2	14.4	14.5	14.7	14.9	15.1
JUN.	13.8	14.0	14.2	14.4	14.5	14.7	14.8	15.0	15.2	15.5	15.7	15.9
JUL.	13.6	13.7	13.9	14.1	14.2	14.4	14.6	14.8	15.0	15.2	15.4	15.7
AUG.	13.1	13.1	13.3	13.4	13.5	13.6	13.7	13.8	13.9	14.0	14.2	14.3
SEP.	12.3	12.3	12.3	12.3	12.3	12.3	12.4	12.4	12.4	12.4	12.5	12.5
OCT.	11.6	11.5	11.4	11.4	11.3	11.2	11.1	11.1	11.0	10.9	10.8	10.8
NOV.	10.8	10.7	10.6	10.5	10.4	10.2	10.1	10.0	9.9	9.8	9.6	9.3
DEC.	10.4	10.2	10.1	9.9	9.7	9.6	9.4	9.3	9.1	9.0	8.7	8.5

*) From: The American Ephemeris and Nautical Almanac for the year 1957. Values are for approximately the 15th of each month.

Table 3. EXTRATERRESTRIAL RADIATION*) EXPRESSED IN INCHES PER DAY

EVAPORATION EQUIVALENT (1 GRAM OF WATER = 590 CALORIES)

MONTH	LATITUDE 26°	28°	30°	32°	34°	36°	38°	40°	42°	44°	46°	48°
JAN.	.364	.354	.335	.317	.300	.279	.260	.241	.221	.203	.184	.167
FEB.	.485	.478	.462	.447	.433	.414	.397	.379	.360	.340	.320	.298
MAR.	.516	.512	.501	.492	.480	.467	.454	.441	.427	.412	.397	.381
APR.	.600	.598	.594	.588	.582	.578	.571	.564	.556	.548	.540	.530
MAY	.620	.620	.622	.623	.623	.622	.622	.620	.619	.617	.614	.610
JUN.	.652	.654	.656	.660	.662	.664	.666	.667	.668	.668	.668	.667
JUL.	.620	.622	.626	.627	.628	.629	.629	.628	.628	.627	.626	.622
AUG.	.588	.587	.586	.582	.580	.574	.570	.564	.558	.552	.544	.536
SEP.	.553	.546	.538	.530	.519	.507	.496	.483	.469	.456	.441	.426
OCT.	.462	.448	.435	.421	.406	.390	.373	.356	.338	.320	.300	.283
NOV.	.398	.380	.362	.345	.327	.307	.289	.270	.250	.230	.211	.191
DEC.	.347	.329	.309	.292	.272	.253	.233	.213	.195	.176	.157	.140

*) From Angot's tables as given in D. Brunt, Physical and Dynamical Meteorology 2nd Ed., 1939 p. 112.

4.4 Sunshine duration measurement

Sunshine duration can be estimated visually, but this is a very crude method, and not satisfactory for the present purpose.

The Weather Bureau employs a mercury switch, which closes or opens a circuit, depending upon radiation intensity. The impulses are recorded on a chart. This instrument is not cheap, required considerable work and attention, and has been known to give trouble.

We recommend the use of the Campbell-Stokes Recorder*, which is a simple and fool-proof instrument. In this device the image of the sun, which is produced by a lens, burns a track in a calibrated strip of paper. The paper is to be renewed each day, and the sunshine hours are easily read off.

4.5 Evapotranspiration formulas and references.

Although evapotranspiration can be related to other climatic variables, it would be wrong to consider it a "derived" or secondary quantity. Evapotranspiration is a primary process in the atmosphere, its intensity determining, in part, such characteristics as: air temperature, soil temperature, moisture content of the air, and moisture content of the soil.

Methods whereby evapotranspiration is estimated fall in three categories:

a/ Empirical methods based on comparison of experimental data and the fitting of arbitrary relations.

b/ Theoretical methods based on the physics of the vapor transfer process.

c/ Theoretical methods based on the physics of the energies involved.

The purpose of this section is to review briefly the existing methods. A much more detailed and excellent review that is much recommended is given in "Evapotranspiration" by W. R. van Wijk and D. A. de Vries, Neth. J. Agr. Sci. 2: 105-119, 1954.

4.51 Empirical formula

A general formula of long standing is:

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* Obtainable from Science Associates, Box 216, Princeton, N. J., $195.00

$$E = a(e_s - e_d)(1 + b.u.)$$

a and b are numerical constants; u is windspeed; e_s is vapor pressure at surface: e_d is vapor pressure at an arbitrary height above the surface. The difficulty with this approach is that, in the case of land surfaces, e_s is immeasurable and that, also, the values of a and b must be determined in each case. This formula, therefore, is not very useful.

4.52 Thornthwaite's formula (1948)

This method was published in "An Approach Toward a Rational Classification of Climate" by C. W. Thornthwaite, The Geogr. Rev. 38: 55-94, 1948. Thornthwaite assumes that the relation between mean monthly temperature and mean monthly evapotranspiration is an expotential one, i. e., on double-logarithmic paper a straight line is obtained. The slope and intercept of this line are determined by the "heat index" of a location, which in turn depends on the mean monthly temperatures.

The formula of Thornthwaite is based on experience with watersheds in the central and eastern United States and has limited value. Where temperature and radiation are strongly correlated such as in temperate, continental climates, the formula works well. In southern latitudes or in maritime climates, the formula does not seem to apply nearly as well. Further, the formula "lags" three or four weeks in the spring and summer because air temperature lags behind radiation, which really determines evapotranspiration.

The formula can be used readily because temperature data are universally available and the calculations are not too difficult.

4.53 Blaney and Criddle formula

This method, used extensively in the West, is cited in "Determining water requirements in irrigated areas from climatological and irrigation data" by H. F. Blaney and W. D. Criddle, USDA-SCS, TP 96, Washington, D. C. 1950.

The monthly value for evapotranspiration is found by:

$$u = \frac{t \times p}{100} \times f$$

u = monthly evapotranspiration in inches.
t = average monthly temperature in ^{o}F.
p = percent day time hours of entire year occurring in month.
f = empirical factor (consumptive use factor)

The value of f is determined in suitable experiments and has been reported for a great number of crops. The value of f is very similar for most crops, excluding some orchard crops and rice.

The Blaney and Criddle formula suffers from similar drawbacks as the Thornthwaite method, namely, that it is based on temperature primarily. The determination of f is not simple and values given are, in some cases, questionable or of local value only.

4.54 Methods based on vapor transfer

The following expression was derived in 1937 by Thornthwaite and Holzmann:

$$E = \frac{k_o^2 (x_1 - x_2)(u_2 - u_1)}{(\log z_2/z_1)^2} \quad g \ sec^{-1} \ cm^{-2}$$

k_o = universal constant
x_1 = vapor density at elevation 1
u_1 = windspeed at elevation 1
z_1 = elevation 1

4.55 Another formula, quite simple and similar to the one given under 4.51 is:

$$E = .20 \ u_2 \ (e_s - e_d) \ mm \ day^{-1}$$

u_2 = windspeed at 2 meters in miles per day
e_s = vapor pressure at surface
e_d = vapor pressure at 2 meters

4.56 A modern formula given by Halstead is:

$$E = .00142 \ (u_{2z} - u_z) \ (e_{2z} - e_z)$$

E = evaporation in cm per hour
u = wind velocity in cm per second
e = vapor pressure in millibars
z = elevation in cm

All such formulas, although perhaps theoretically sound, are at the present time not practical for the agronomist because the variables have to be measured with extreme precision and with instrumentation that is still under development.

4.57 Formulas based on the energy balance

In this approach, the energy received by a surface through radiation must equal the energy used for evaporation plus that used for heating the air, plus that for heating the soil and any extraneous or advective energy. The latter two can safely be neglected for daily balances, and also for a monthly balance when precision does not have to be better than 5%. The application of this idea comes down to estimating or measuring the energy received by a surface, and deciding how this amount is to be distributed over the heating of the air and evaporation. It can be assumed that said partition takes place according to the so-called Bowen ratio, a fraction depending on temperature and vapor pressure at the surface and at some height above it. Penman suggested in 1948 a novel method by which certain practical difficulties associated with this method might be overcome. The method was first published in : "Natural evaporation from open water, bare soil and grass" by H. L. Penman. Proc. Roy. Soc. A., 193, 120-145, 1948. A more recent reference is "Estimating evaporation" Trans. Am. Geoph. Un. 37: 43-46. 1956. This method consists of estimating the amount of radiative energy gained by the surface, called H and expressed in mm water. Then he proceeds as follows:

$E_a = 0.35\ (e_a - e_d)\ (1 + 0.0098\ u_2)$ mm day $^{-1}$
E_a = an auxiliary quantity
u_2 = windspeed at 2 m in miles day $^{-1}$
e_a = saturation vapor pressure of air in mm Hg
e_d = actual vapor pressure of air in mm Hg

further:

$$E_T = \frac{H + 0.27\ E_a}{\Delta + 0.27}$$

E_T = evapotranspiration in mm day $^{-1}$

$E_T = \left.\frac{de}{dt}\right|\ T_a$; e is vapor pressure in mm Hg; T is temperature in $^{\circ}F$;

T_a is air temperature in $^{\circ}F$.

The formula as given is not quite what is used by Penman, but a slight modification by the author.

H can be estimated as follows:

$$H = R_A(1-r)\ (0.18 + 0.55\ n/N) - \sigma T_a^4 (0.56 - 0.92\sqrt{e_d})\ (0.10 + 0.90\ n/N)$$

R_A = mean monthly extraterrestrial radiation in mm day $^{-1}$

r = reflection coefficient

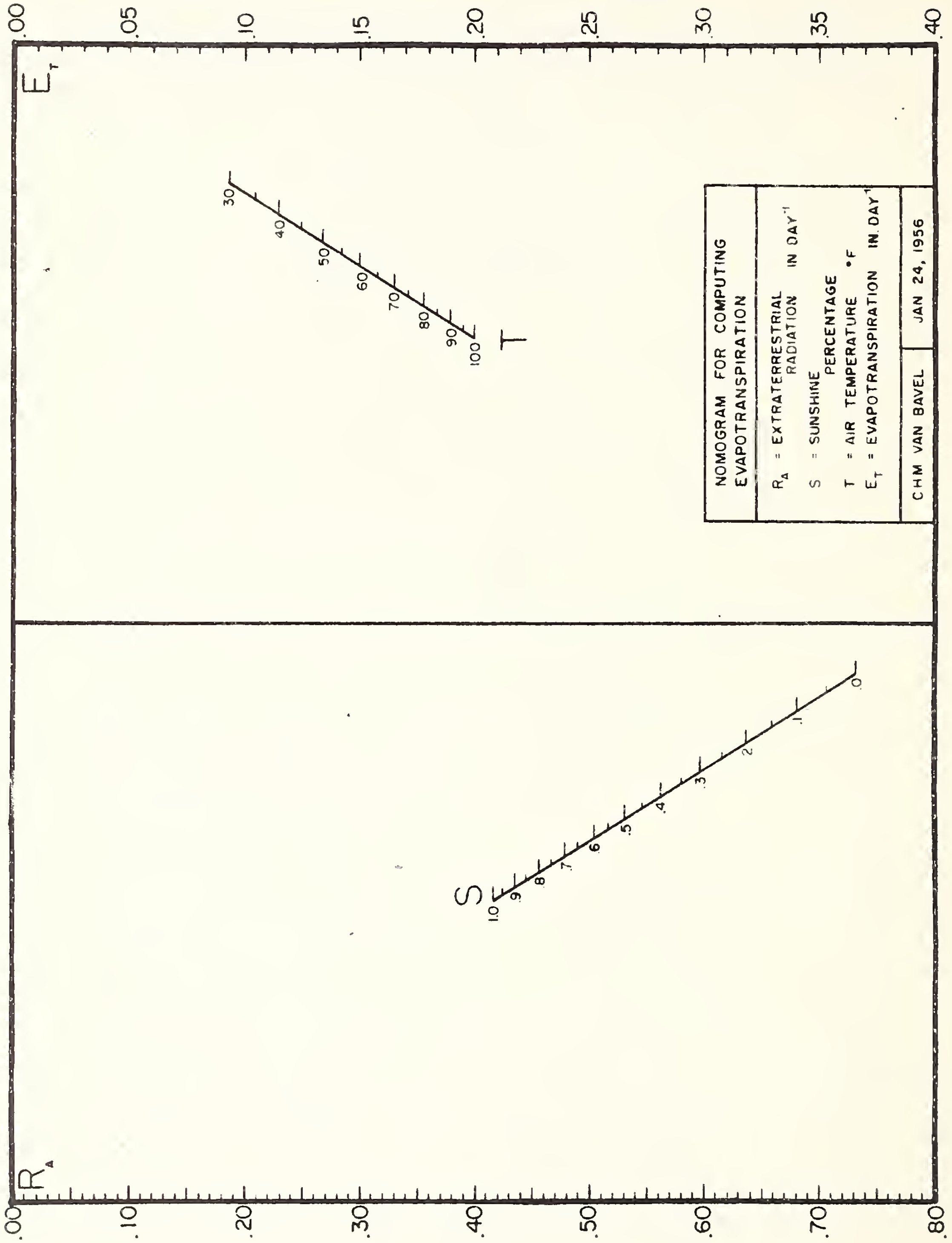
n/N = sunshine percentage

σ = Boltzmann constant

H is actually the net radiation and can be measured directly.

5. Experimental evidence so far lends the most support to the Penman Formula as a universal method. Its use is not simple, but fortunately it seems that evaporation is a conservative phenomenon; that is, it is quite uniform over large areas, and therefore, it does not have to be calculated for many points.

It is important to realize that all the above formulas apply only to large uniform areas. Moreover, they give maximum or potential values; that is, soil moisture content is not limiting and the area is fully covered with vegetation.



NOMOGRAM FOR COMPUTING EVAPOTRANSPIRATION

R_A = EXTRATERRESTRIAL RADIATION IN DAY^{-1}

S = SUNSHINE PERCENTAGE

T = AIR TEMPERATURE °F

E_T = EVAPOTRANSPIRATION IN. DAY^{-1}

C H M VAN BAVEL

JAN 24, 1956